What We Can Learn About Aerosols from EOS-MISR Multi-Angle Remote Sensing Observations over Ocean

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Multiangle, multispectral remote sensing observations, such as those anticipated from the Earth Observing System (EOS) Multiangle Imaging SpectroRadiometer (MISR), promise to significantly improve our ability to constrain aerosol properties from space.

Recent advances in modeling the Earth's climate have brought us to a point where the contributions made by aerosols to the global radiation budget noticeably affect the results. Knowledge of both aerosol optical depth and the microphysical properties of particles is needed to adequately model aerosol effects. The radiance effects of aerosols must also be accounted for when retrieving surface properties from satellite observations. This talk explores the ability of multiangle, multi-spectral remote sensing observations anticipated from the EOS MISR instrument, to retrieve aerosol optical depth and information about mixes of particle types, globally, at 17.6 km spatial resolution. The instrument is scheduled for launch into a 10:30 AM, sun-synchronous polar orbit in 1999.

MISR will measure the upwelling visible radiance from Earth in 4 spectral bands centered at 446, 558, 672, and 866 nm, at each of 9 emission angles spread out in the forward and aft directions along the flight path at ±70.5°, ±60.0°, ±45.6°, ±26.1°, and nadir. The spatial sampling rate is 275 meters in the cross-track direction at all angles. Over a period of 7 minutes, a 360 km wide swath of Earth comes into the view of the cameras at each of the 9 emission angles, providing a wide range of scattering angle coverage for each surface location. In addition to aerosol studies, the data will be used to characterize surface albedo and bi-directional reflectance, and cloud properties. Global coverage will be acquired about once in 9 days at the equator; the nominal mission lifetime is 6 years.

Our aerosol retrieval approach involves separating the data into cases where the surface is dark water, dense dark vegetation (DDV), heterogeneous land, or "other" (Martonchik et al., 1998). Retrievals will be performed on data in the first 3 categories. For dark water retrievals, we use the red and near-infrared bands only, where the surface is darkest, and we model surface glitter and whitecap effects as a function of estimated surface wind speed, using standard models. We use the formalism of statistical chi-squared tests to compare the data with simulated instrument radiances in performing the retrieval. Simulations are done for many natural conditions, based on climatological expectations about atmospheric and surface properties.

According to simulations over cloud-free, calm ocean, for pure particles with natural ranges of optical depth, particle size, and indices of refraction, we can retrieve column optical depth for all but the darkest particles, to an uncertainty of at most 0.05 or 20%, whichever is larger, even if the particle properties are poorly known (Kahn et al., J. Geophys. Res. 1997; 1998). For one common particle type, soot, constraints on the optical depth over dark ocean are very poor. The simulated measurements also allow us to distinguish spherical from non-spherical particles, to separate two to four compositional groups based on indices of refraction, and to identify three to four distinct size groups between 0.1 and 2.0 microns characteristic radius at most latitudes. The technique is most sensitive to particle microphysical properties in the "accumulation mode" sizes, where particle scattering undergoes the transition from Rayleigh to large-particle regimes for the MISR wavelengths.

Based on these results and data from monthly global aerosol climatologies, we expect to distinguish air masses containing about 10 commonly occurring mixtures of aerosol types, routinely and globally, with multiangle remote sensing data. Such data complements *in situ* and field data, which can provide details about aerosol size and composition locally.

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To account for the effects of aerosols in Climate Models:

- Need the column extinction **optical depth** (τ_a)

  -- Currently the state-of-the-art for operational satellite retrievals

- Need mean effective aerosol **microphysical properties**

  -- Single scattering **phase function** and **albedo**

  -- These map to **Size Distribution** (r_a), **Shape**, and **Indices of Refraction** (nr, ni)

- Need aerosol **vertical distribution**

Summary: Need constraints on [τ_a, r_a, **nr, ni**] & shape

New Multiangle Capability -- More Information about Aerosols

How will MISR contribute to the global aerosol picture needed for climate change studies?

Based on simulations over cloud-free, calm ocean, for pure particle types:

- **Aerosol Extinction Optical Depth (τ_a)**

-- Determined to at least 0.05 or 20%, whichever is larger, for common aerosol types except soot, even when the particle microphysical properties are poorly known.

- **Particle Size (r_a)**

-- "Small," "Medium," and "Large" size discrimination across Accumulation Mode sizes -- key for vis spectrum

- **Indices of Refraction (nr, ni)**

-- Two to four compositional groups

- **Spherical vs. Nonspherical** for Sahara dust indices

- **Poorer Sensitivity for ni >~ 0.008 (Black Carbon)**

How can MISR contribute?

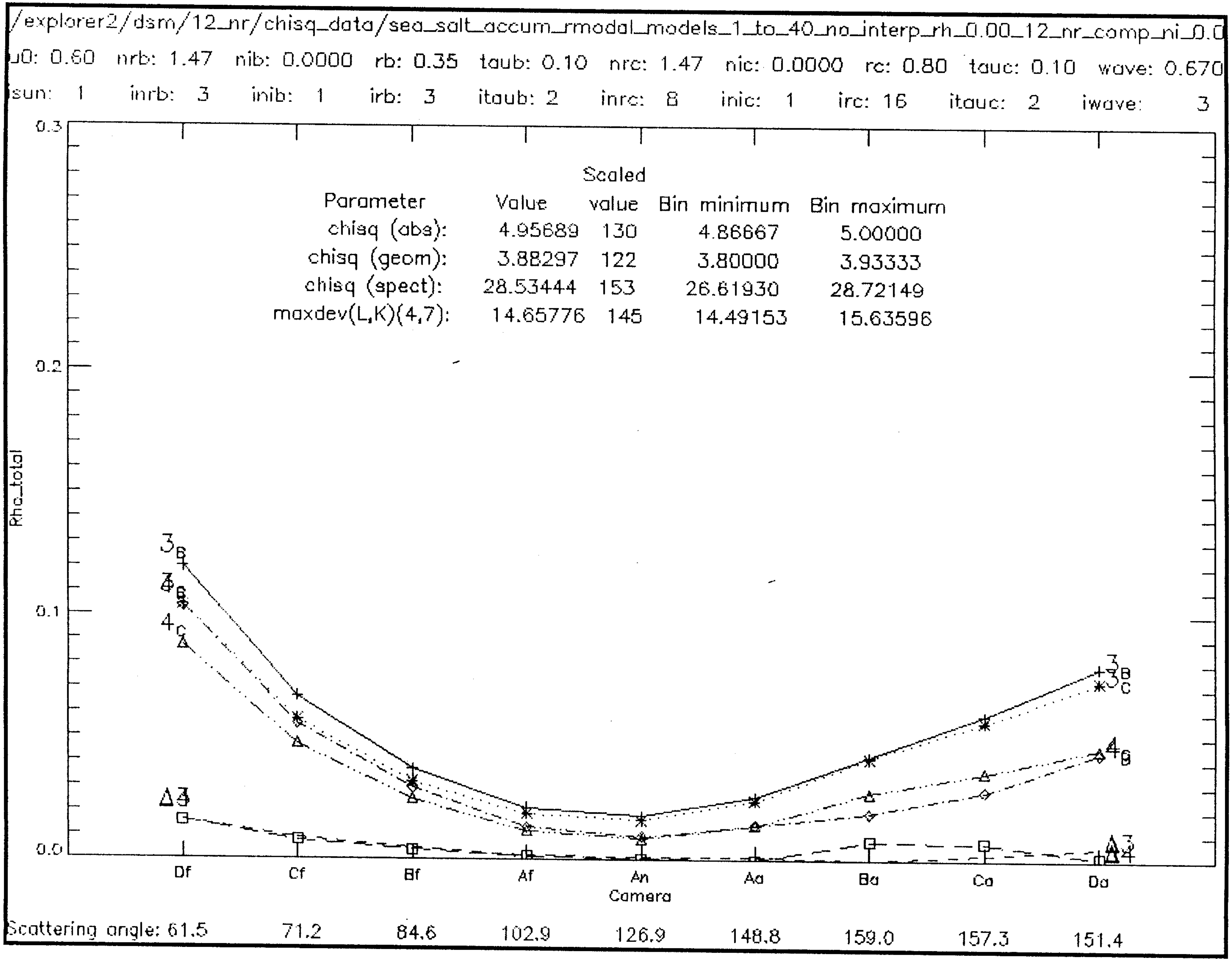
- **Can not** in general **nail down everything** we need to know to model the effects of aerosols, even over cloud-free, calm ocean, without introducing other information

- **Can distinguish air masses** containing different aerosol types – a major step beyond current operational satellite aerosol retrievals, which obtain only optical depth, based on entirely assumed particle properties

Use **MISR to get the large-scale, time-varying picture** of air masses containing different aerosol types

Rely on **field measurements to give detailed microphysical properties** of aerosol within each air mass

====> **Complementary Efforts**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isun: 1 inrb: 3 inib: 1 irb: 3 itaub: 2 inrc: 8 inic: 1 irc: 16 itauc: 2 iwave: 3
Scaled
Parameter Value value Bin minimum Bin maximum
chisq (abs): 4.95689 130 4.86667 5.00000
chisq (geom): 3.88297 122 3.80000 3.93333
chisq (spect): 28.53444 153 26.61930 28.72149
maxdev(L,K)(4,7): 14.65776 145 14.49153 15.63596
Rho_total
0.3
0.2
0.1
0.0
Df
Cf
Bf
Af
An
Aa
Ba
Ca
Da
Camera
Scattering angle: 61.5
71.2
84.6
102.9
126.9
148.8
159.0
157.3
151.4

Evaluating Agreement Between Comparison Models and "Measurements"

4 Parameters are used to summarize the information in **18 Measurements**

χ^2_{abs} is defined as:

$$\chi^2_{abs} = \frac{1}{N\langle w_k \rangle} \sum_{l=3}^{4} \sum_{k=1}^{9} \frac{w_k \left[\rho_{meas}(l,k) - \rho_{comp}(l,k) \right]^2}{\sigma^2_{abs}(l,k)} \tag{1}$$

where ρ_{meas} is the simulated "measured" radiance, ρ_{comp} is the simulated radiance for the "assumed" comparison model, l and k are the indices for wavelength band and camera, N is the number of measurements included in the calculation, and σ_{abs} is the absolute measurement error in the radiance. w_k is the weight for terms related to camera k, and $<w_k>$ is the average of the weights for all the cameras included in the sum.

χ^2_{geom} is defined as:

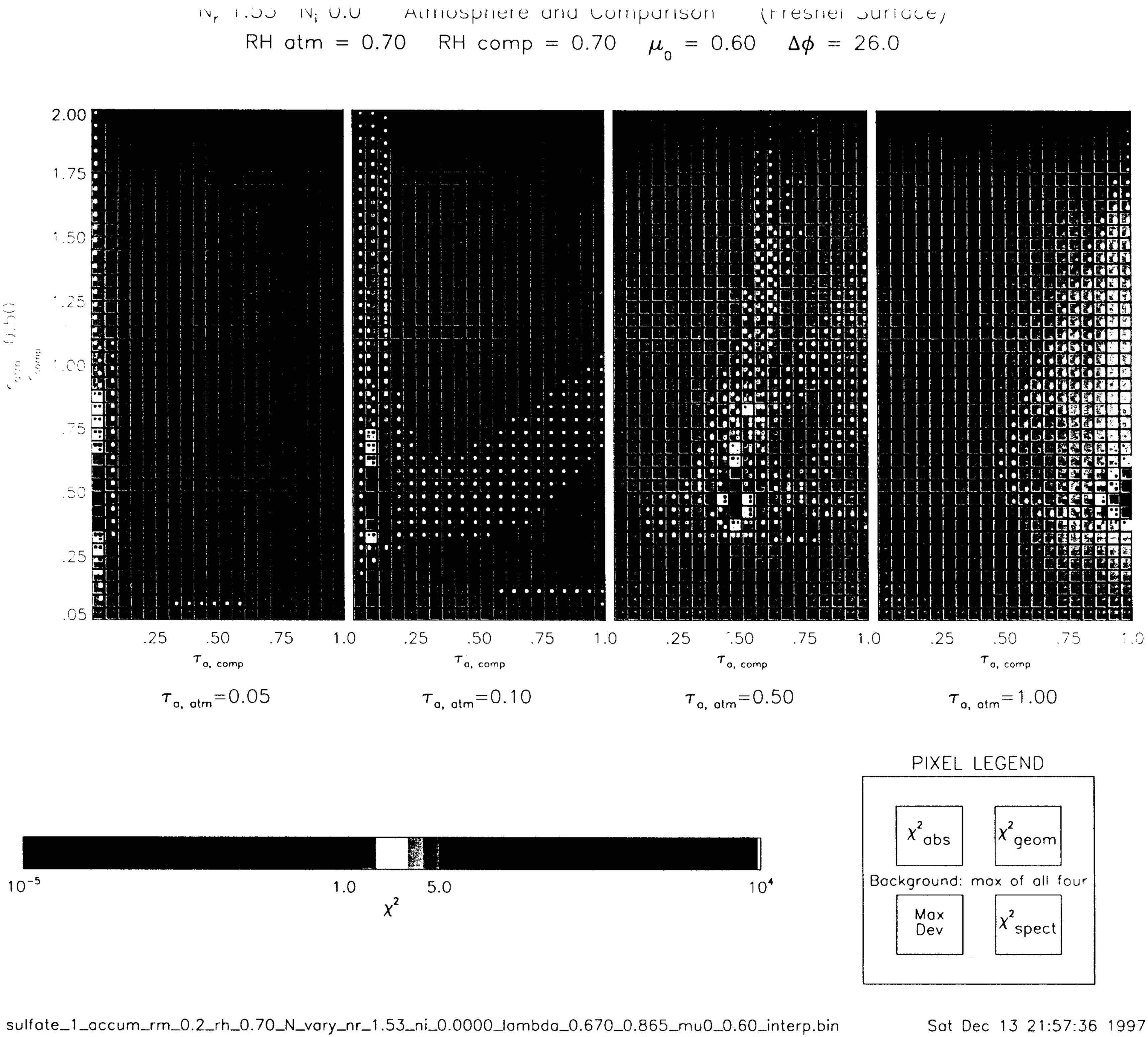
$$\chi^2_{geom} = \frac{1}{N\langle w_k \rangle} \sum_{l=3}^{4} \sum_{\substack{k=1 \\ k \neq nadir}}^{9} \frac{w_k \left[\frac{\rho_{meas}(l,k)}{\rho_{meas}(l,nadir)} - \frac{\rho_{comp}(l,k)}{\rho_{comp}(l,nadir)} \right]^2}{\sigma^2_{geom}(l,k)} \tag{2a}$$

Here σ^2_{geom} is the uncertainty in the camera-to-camera equivalent reflectance :

$$\sigma^2_{geom}(l,k) = \frac{\sigma^2_{cam}(l,k)}{\rho^2_{meas}(l,nadir)} + \frac{\sigma^2_{cam}(l,nadir)\ \rho^2_{meas}(l,k)}{\rho^4_{meas}(l,nadir)} \tag{2b}$$

$\sigma_{cam}(l,k)$ is the contribution of (band l, camera k.) to the camera-to-camera relative calibration reflectance uncertainty.

Also, χ^2_{spec} (similar to χ^2_{geom}, but normalized to band 3) and χ^2_{maxdev}, which is largest term in (1).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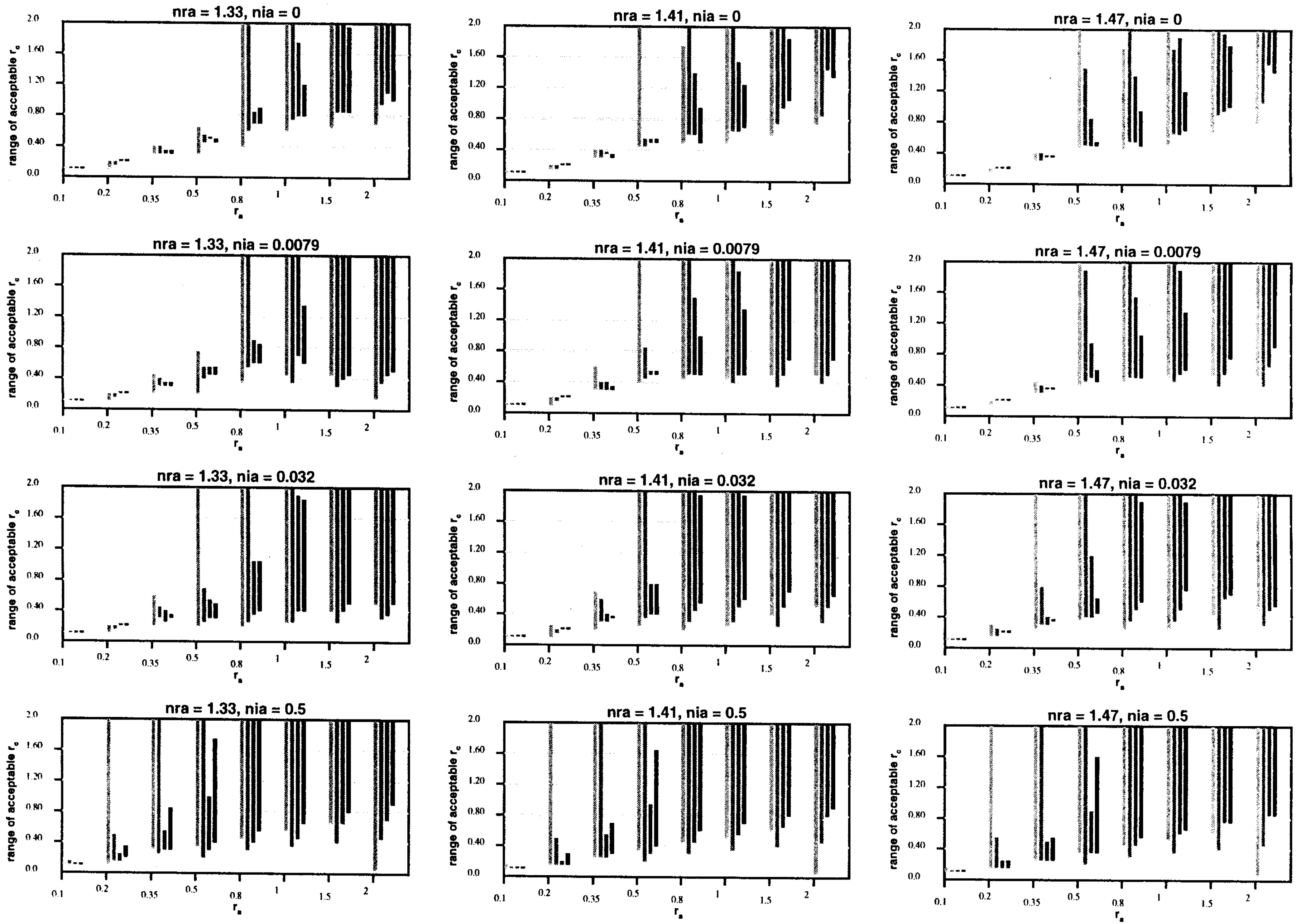
2.00
1.75
1.50
1.25
1.00
.75
.50
.25
.05
.25 .50 .75 1.0
τa, comp
τa, atm=0.05
τa, atm=0.10
τa, atm=0.50
τa, atm=1.00
10^-5
1.0
5.0
10^4
χ²
PIXEL LEGEND
χ² abs
χ² geom
Background: max of all four
Max Dev
χ² spect
sulfate_1_accum_rm_0.2_rh_0.70_N_vary_nr_1.53_ni_0.0000_lambda_0.670_0.865_mu0_0.60_interp.bin
Sat Dec 13 21:57:36 1997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nra = 1.47, nia = 0.032
nra = 1.33, nia = 0.5
nra = 1.41, nia = 0.5
nra = 1.47, nia = 0.5
range of acceptable r_c
0.0
0.40
0.80
1.20
1.60
2.0
r_a
0.1
0.2
0.35
0.5
0.8
1
1.5
2

The Need for a Climatological Retrieval

The "Generic" Retrieval obtains column mean weighted aerosol properties with a minimum of assumptions

- Indicates the "Information Content" of the data
- May not produce properties that apply to any particles actually in the atmosphere
  - -- Difficult to check against field measurements
  - -- Difficult to check against expected sources (models)

===> Natural populations are mixes

The "Climatological" Retrieval assumes pure particle properties and derives the range of mixes that match the observations

- The results depend on the quality of the assumed climatology
- Needed to identify air mass source regions
- Needed to track the evolution of air mass as they are advected downstream from sources
- Needed to compare MISR data with aerosol transport models
- Needed to compare MISR data with in situ sampling

Monthly, Global Aerosol Transport Model Results Used

Aerosol Type	Source	Reference	Spatial Resolution	Quantities Reported	Factor Used to Convert Mass to τ
Accumulation and Coarse **Mineral Dust**	GISS	Tegen & Fung (1995)	4° x 5°	Total Column Dust Optical Depth, regrouped into 2 size bins: < 1 micron (accumulation) 1 to 10 micron (coarse)	1.5 m^2/gm (accum. mode); 0.3 x m^2/gm (coarse mode)
Sea Salt	GISS	Tegen et al. (1997)	4° x 5°	Total Column Aerosol Optical Thickness	0.3 m^2/gm
Sulfates	LLNL	Liousse et al. (1996)	~ 4.5° x 7.5°	Column Mass Load (gm/m^2)	8.5 m^2/gm
Carbonaceous Particles	GISS	Liousse et al. (1996)	4° x 5°	Total Column Aerosol Optical Thickness	8.0 m^2/gm
Black Carbon	GISS	Liousse et al. (1996)	4° x 5°	Total Column Aerosol Optical Thickness	9. m^2/gm

Major Climatological Particle Mixing Groups

Classification	Component 1	Component 2	Component 3	Component 4	Color
1. Carbonaceous + Dusty Maritime	Sulfate	Sea Salt	Carbonaceous	Accumulation Mode Dust	Blue
2. Dusty Maritime + Coarse Dust	Sulfate	Sea Salt	Accumulation Mode Dust	Coarse Dust	Yellow
3. Carbonaceous + Black Carbon Maritime	Sulfate	Sea Salt	Carbonaceous	Black Carbon	Green
4. Carbonaceous + Dusty Continental	Sulfate	Accumulation Mode Dust	Coarse Dust	Carbonaceous	Red-Brown
5. Carbonaceous + Black Carbon Continental	Sulfate	Accumulation Mode Dust	Carbonaceous	Black Carbon	Gray

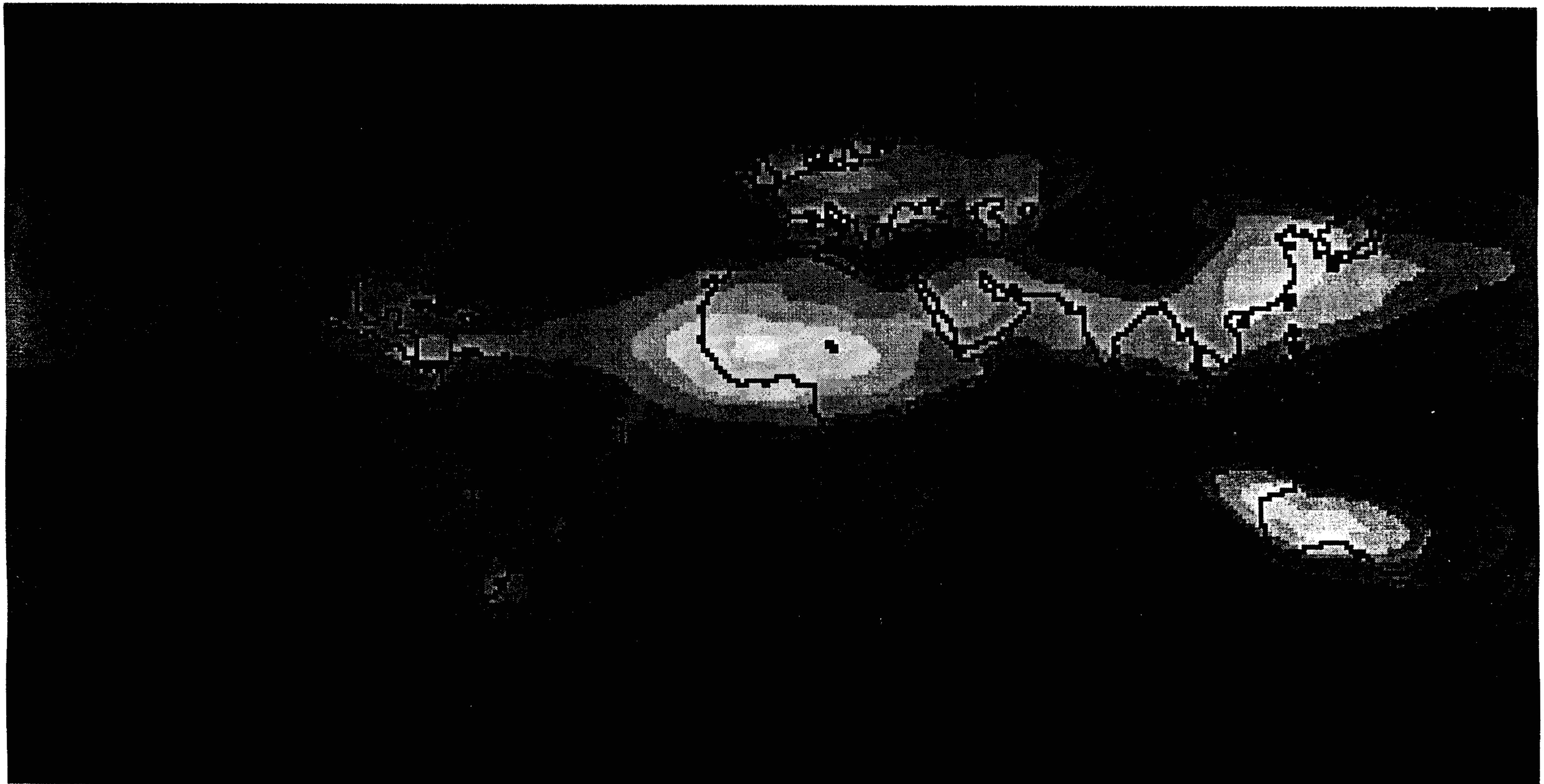

lat=-89 lon=-180 pixel=4 Tau_tot=0.007322 month=January


lat=-89 lon=-180 pixel=22 Tau_tot=0.005465 month=July

Particle Mixture Classification Scheme

Classification	Component 1	Component 2	Component 3	Component 4	Color
1. Carbonaceous + Dusty Maritime	**Sulfate**	**Sea Salt**	**Carbonaceous**	**Accumulation Mode Dust**	**Blue**
1a.	**0.67**	0.13	0.10	0.10	
1b.	0.41	0.13	**0.27**	**0.19**	
1c.	0.40	**0.32**	0.17	0.11	
2. Dusty Maritime + Coarse Dust	**Sulfate**	**Sea Salt**	**Accumulation Mode Dust**	**Coarse Dust**	**Yellow**
2a.	**0.52**	0.17	0.21	0.10	
2b.	0.29	0.13	**0.39**	**0.19**	
3. Carbonaceous + Black Carbon Maritime	**Sulfate**	**Sea Salt**	**Carbonaceous**	**Black Carbon**	**Green**
3a.	**0.51**	0.18	0.26	0.05	
3b.	0.35	0.10	**0.47**	**0.08**	
4. Carbonaceous + Dusty Continental	**Sulfate**	**Accumulation Mode Dust**	**Coarse Dust**	**Carbonaceous**	**Red-Brown**
4a.	**0.61**	0.21	0.05	0.13	
4b.	0.40	**0.35**	0.09	**0.16**	
4c.	0.22	**0.51**	**0.16**	0.11	

5. Carbonaceous + Black Carbon Continental	Sulfate	Accumulation Mode Dust	Carbonaceous	Black Carbon	Gray
5a.	**0.59**	0.12	0.23	0.06	
5b.	0.25	0.12	**0.54**	0.09	
5c.	0.44	**0.23**	**0.26**	0.07	



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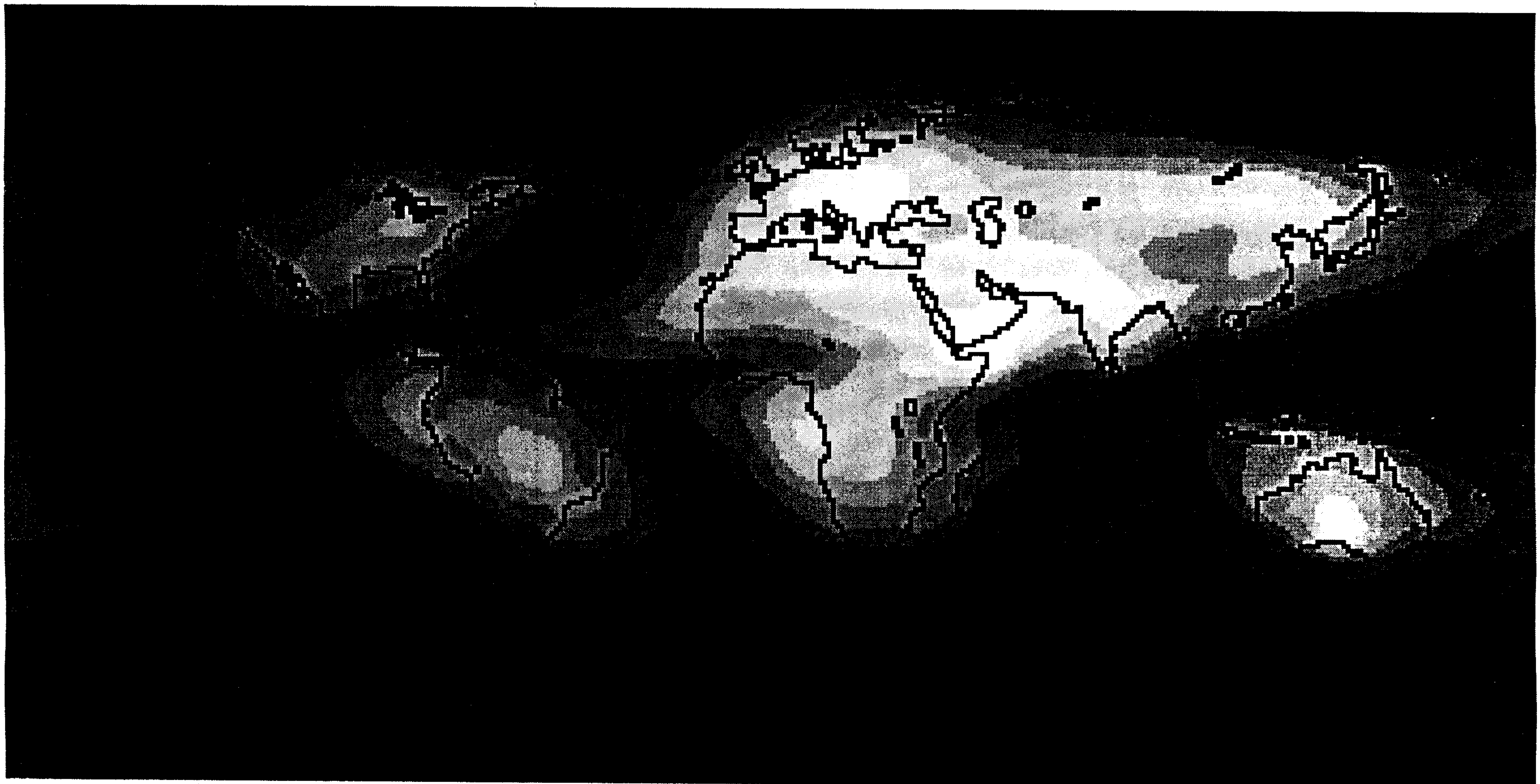
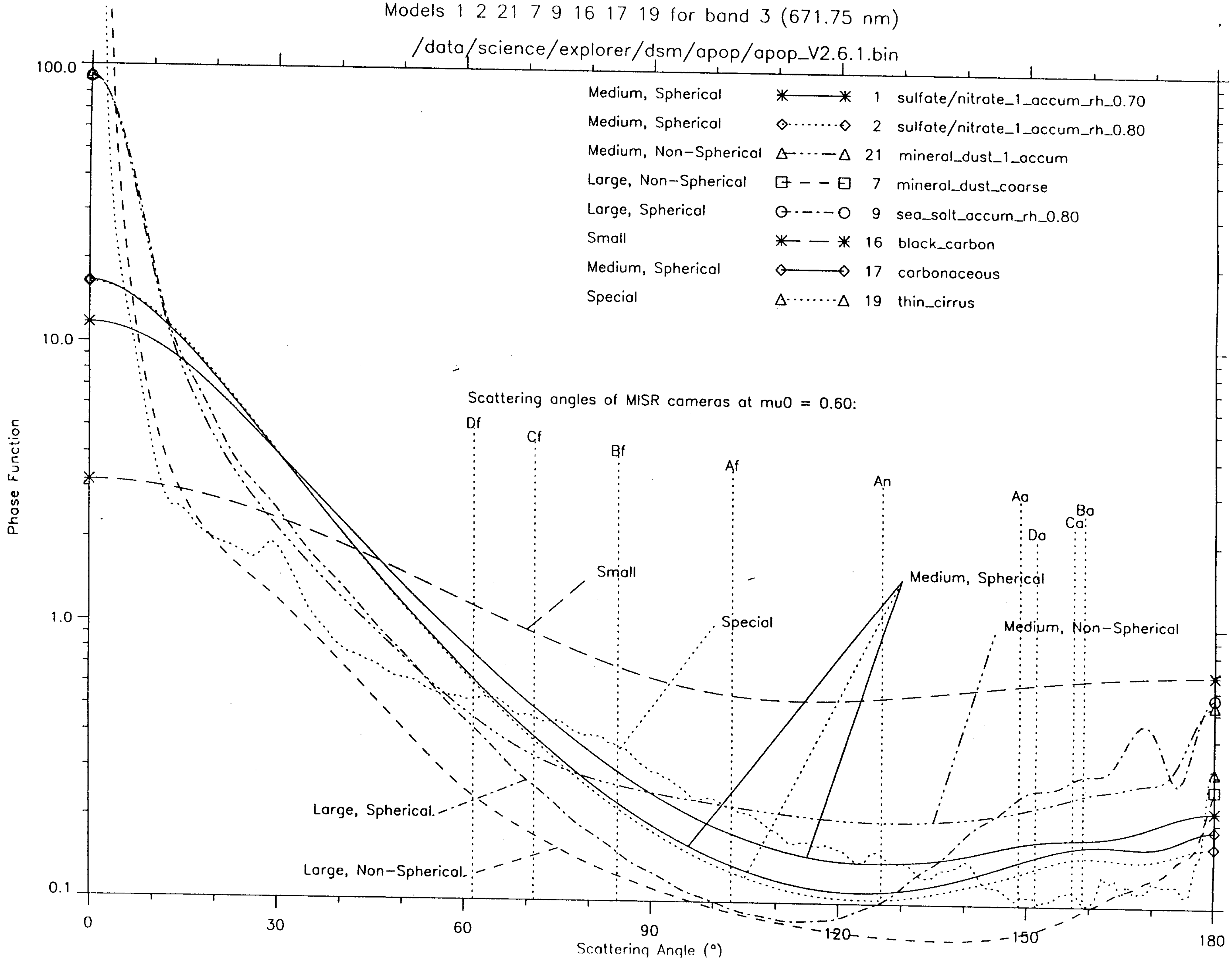


lat=-89 lon=-180 pixel=12 Tau_tot=0.005465 month=July

Assumed Physical Properties of Component Particles§

	n_r	n_i	r_c	ω_0	Size / Shape Category
Thin Cirrus	1.31	0.0	>50.	1.0	Special
Sea Salt	1.35	0.0	0.61	1.0	Large Spherical
Sulfate (Land)	1.46	0.0	0.08	10.	Medium Spherical
Sulfate (Ocean)	1.39	0.0	0.10	1.0	Medium Spherical
Carbonaceous	1.43	0.0035	0.13	0.98	Medium Spherical
Mineral Dust (Accumulation Mode)	1.53	0.0045	0.47	0.91	Medium Nonspherical
Mineral Dust (Coarse Mode)	1.53	0.0045	1.90	0.73	Large Nonspherical
Black Carbon	1.75	0.440	0.012	0.17	Small

§ Optical properties reported for MISR Band 3 (670 nanometers). For hygroscopic particles, the hydrated values are shown.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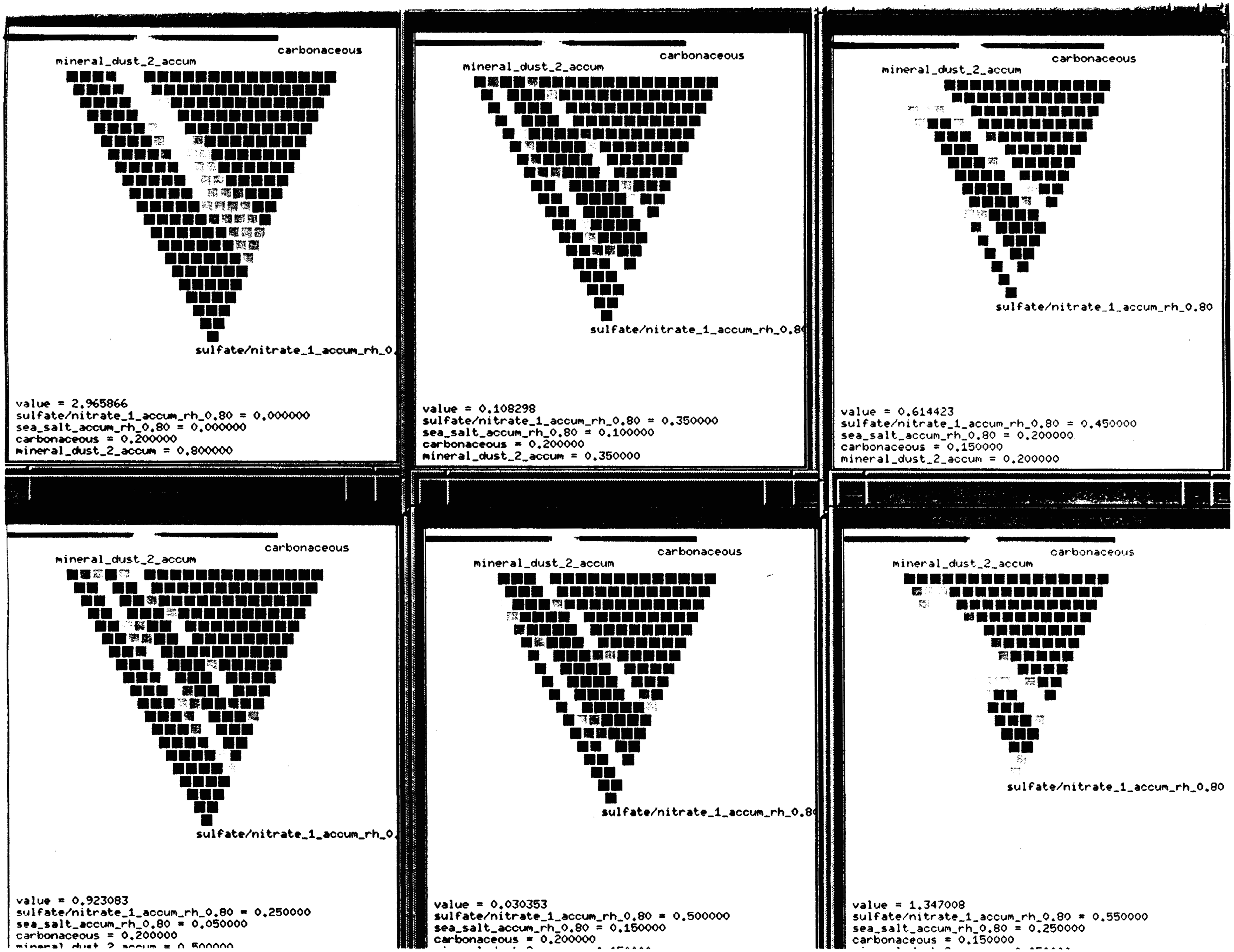
Medium, Spherical 1 sulfate/nitrate_1_accum_rh_0.70
Medium, Spherical 2 sulfate/nitrate_1_accum_rh_0.80
Medium, Non-Spherical 21 mineral_dust_1_accum
Large, Non-Spherical 7 mineral_dust_coarse
Large, Spherical 9 sea_salt_accum_rh_0.80
Small 16 black_carbon
Medium, Spherical 17 carbonaceous
Special 19 thin_cirrus
Scattering angles of MISR cameras at mu0 = 0.60:
Df
Cf
Bf
Af
An
Aa
Da
Ca
Ba
Small
Special
Medium, Spherical
Medium, Non-Spherical
Large, Spherical
Large, Non-Spherical
Phase Function
100.0
10.0
1.0
0.1
0
30
60
90
120
150
180
Scattering Angle (°)



carbonaceous
mineral_dust_2_accum
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sea_salt_accum_rh_0.80 = 0.000000
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mineral_dust_2_accum = 0.800000
carbonaceous
mineral_dust_2_accum
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sulfate/nitrate_1_accum_rh_0.80 = 0.350000
sea_salt_accum_rh_0.80 = 0.100000
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mineral_dust_2_accum = 0.350000
carbonaceous
mineral_dust_2_accum
sulfate/nitrate_1_accum_rh_0.80
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carbonaceous
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sulfate/nitrate_1_accum_rh_0.80 = 0.550000
sea_salt_accum_rh_0.80 = 0.250000
carbonaceous = 0.150000

Overall Program for MISR Pre-Launch Sensitivity Studies

1. Sensitivity to the difference between **Spherical and NonSpherical** Particles with "Mineral Dust" indices of refraction and particle size ranges.

JGR 102, D14, pages 16,861 - 16,870.

2. Sensitivity to the differences in **optical depth**, **characteristic radius**, and **indices of refraction** for Pure Particle Types.

JGR 103, D24, pages 32,195 - 32,213.

3. Sensitivity to natural **Mixes** of Particles.

JGR, to be submitted, Sept., 1999.

4. Constraints that MISR, MODIS, SAGE III, and CERES can make to the Cloud-free **Reflected Solar Radiation Flux**.

Joint Project: Kahn, West, Ackerman, Clothiaux, Martonchik, Strahler, Schaaf, Strugnel, Lucht

In progress.

5. **AirMISR Retrieval** Over Dark Water.

In progress.